January, 1995
NSRP 0439

SHIP PRODUCTION COMMITTEE
FACILITIES AND ENVIRONMENTAL EFFECTS
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THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

1995 Ship Production Symposium

Paper No. 4: Tee-Beam Manufacturing Analysis: Producibility of Panel Stiffening Elements

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JAN 1995**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **The National Shipbuilding Research Program, 1995 Ship Production Symposium: Paper No. 4: Tee-Beam Manufacturing Analysis: Producibility of Panel Stiffening Elements**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230 - Design Integration Tower Bldg 192 Room 128 9500 MacArthur Blvd Bethesda, MD 20817-5700**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**24**	

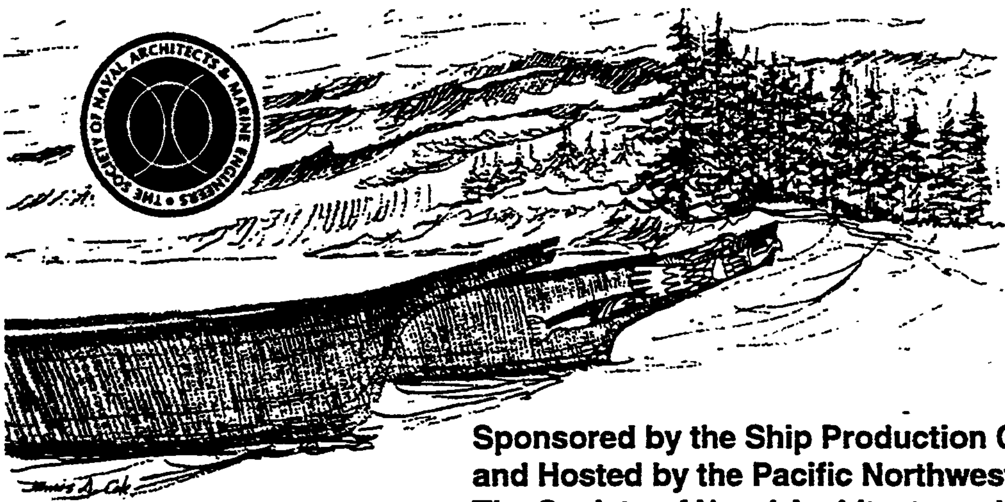
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

0439

1995 SHIP PRODUCTION SYMPOSIUM

Commercial Competitiveness for Small and Large North American Shipyards

Seattle, Washington
The Westin Hotel
January 25-27,1995



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601 PAVONIA AVENUE, JERSEY CITY, NJ 07306
Paper presented at the 1995 Ship Production Symposium
Westin Hotel, Seattle, Washington, January 25-27, 1995

Tee-Beam Manufacturing Analysis: Producibility of Panel Stiffening Elements

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ABSTRACT

This paper analyzes the manufacturing of tee shapes for stiffening ship structure. The traditional method of deflanging hot-rolled I-beams (producing I/T shapes) has been compared to the practice of fabricating tee-shapes from plate. A group of more than 1700 I/T shapes, used in the DDG-51 class vessel was used for comparisons. To produce the I/T shapes for one DDG, flanges are stripped from more than 700 tonnes (690 long tons) of I-beams. The flange material removed amounts to 25% of the weight of the original I-beams, totaling approximately tonnes 172 tonnes (170 tons). This represents a material loss of 25%, easily in excess of $90,000.

Prior review of design criteria for several DDG stiffened plate structures showed that fabricated tees could replace I/T shapes, resulting in weight savings averaging 18%, while still maintaining required strength. An evaluation of methods to produce tee sections was undertaken and the concept of “net shape” fabrication of tee stiffeners was discussed. Both fabricating and stripping methods were considered including newer technologies such as plasma cutting and laser cutting and welding. Mock-up testing was performed using several candidate technologies and the results compared. Plasma-arc cutting reduced distortion on 12.2m (40 ft) test beams by 50% compared to oxyfuel methods. Economic analysis revealed that fabricated tees were less costly to produce than deflanged I-beams, and that handling functions were the greatest cost element of the traditional oxyfuel cutting methodology.

INTRODUCTION AND SCOPE

The information presented here is summarized from the final report of a project funded by the National Shipbuilding Research Program (NSRP #7-91-4). The project was undertaken to compare the relative merits of various schemes for producing panel stiffeners, considering design aspects of fabricated tees versus those stripped from I-beams, and evaluating various methods of producing tee shapes, considering current as well as new technologies. Although fabricated tees may offer some benefits, it is not a foregone conclusion that fabrication is the best approach for every situation. Thus, the quality and relative economies offered by the various processes for both stripping and welding have been considered.

Most combatant ship designs have required tee shapes for stiffening panels (decks, shells, and bulkheads). Typical mill practice involves splitting I-beams down the center of the web, e.g., a 304 mm (12 in)deep I is split into two 152mm(6in)tees, as in Figure 1. This does not provide a shape with the best section properties for ship panel stiffening, since I-shapes are primarily optimized for building construction. A convenient solution has been the traditional approach of removing one pair of flanges, so that the 304 mm (12 in) I becomes a 304 mm (12 in) tee, as in Figure 2. This yields a section with adequate properties for ship panel stiffening, and provides a readily available source of material of convenient length for processing. Although this requires minimal labor

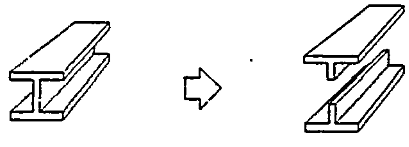

Figure 1. Split I-beam

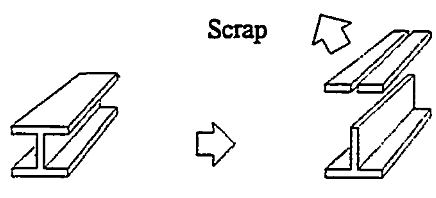

Figure 2. Stripped I-beam

input on the part of the shipyards, it produces a significant amount of scrap material. Also, current production methods frequently cause distortion or damage to the members.

Since the design process can yield values for section properties (the “design shape”) which are not necessarily exactly those of a section available from steel producers, the “next larger” available shape is chosen. Flange and web thicknesses, and widths of available shapes, may also be disproportionte to those of the design shapes. Thus, the convenience of selecting from a catalog results in greater weight and cost. The alternative is to design a shape to be built from plate. Plausibly, plate material is available in a greater range of thicknesses, so that a fabricated tee section could be made with dimensions conforming more closely to those of the design shape. Furthermore, rolled plate material thickness, and therefore weight can be more accurately controlled by steel producers, allowing better conformance to design weight requirements.

Fabricating tees from plate is not at all new or unique,[12.34,5] but has been limited to the X&emt?S production of tee sections where the section size or shape is not available as a hot-rolled I-bearn, especially in the case of deep webframes, or in the allowed case of extremely lightweight sections Usually, custom production of mid-range sections has not been considered cost-effective. There can be several reasons for this, especially when typical shipyard hand-lit and manual or semi-automatic welding methods are used:

- A wide variety might be needed with perhaps little repetition of specific designs,
- Desiging custom shapes adds time to the design phase of the ship,
- Estimated yard labor costs are typically high compared to steel costs,
- Traditional fit-up and tacking of flange to web is viewed as difficulty and
- Traditional manual and semi-automatic welding methods are labor intensive and produce excessive distortion.

Newer welding technologies, such as laser welding and high-frequency resistance welding have challenged these assumptions, and mechanized equipment for producing tees has been continuously improved but neither have made significant inroads into shipbuilding practice. Increasing mechanization and computer integrated manufacturing (CIM) will impact this decision process in the fixure.

PROBLEM STATEMENT

I-beam stripping is typically done using the dual-torch Oxyfuel Cutting (OFC) process, with some sort of mechanized gantry or other device to move the torches over the beams. While this equipment is simple and reliable, the use of the OFC process tends to result in certain characteristic problems which frequently require rework as shown in Figure 3. Unacceptable warpage (camber) is caused by the high heat input associated with OFC. Webs maybe damaged by gouges due to errors in torch tracking. Frequently, the torches are offset from the web to avoid this damage; this practice leaves excess material and weight and can make welding of a tee to a panel more difficult especially when mechanized panel line equipment is used. Also, 25% of the purchased material is turned into scrap.

Hot rolled shapes are manufactured to criteria given by ASTM A-6[26], which specifies tolerances for overall dimensions (such as section depth), allowable camber, flange-to-web tilt alignment of the web with the centers of flanges, and other criteria. The tolerance limits of A-6 may exceed the limitations of fabrication documents for structure alignment. In some cases, A-6 allows enough offset that webs maybe off-center in different directions by more than the thickness of the web material. Sections are allowed a difference in depth that sometimes exceeds flange thickness. Shown in Figure 4, these conditions are often discovered when tees are butted together at unit erection and usually require rework of some sort (patching weld build-up, etc.). Imposing stricter tolerances on rolling mills causes costs to increase. Fabricated shapes can be built far more accurately as a matter of routine.

The use of I/T shapes may induce a weight penalty on vessel design whereas a fabricated shape can

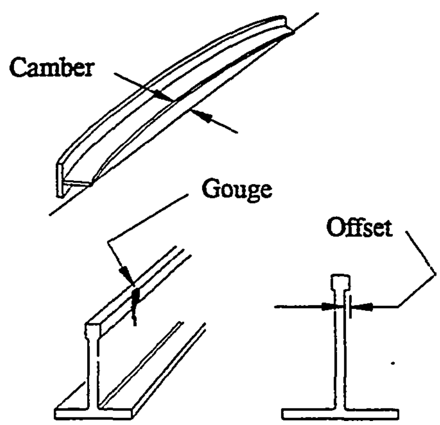

Figure 3. Problems in OFC Deflanging

produce needed properties at reduced weight. The NSRP report includes a design review which calculated the true size of sections required[30] for stiffening several deck bulkhead and shell assemblies. Using these calculated design shapes, fabiricated tees were designed from plate material using thickness commonly available. The fabricated tees had the same outside dimensions as the I/T's in use. In every case, these fabricated tees weighed less than the I/T's, with an average weight savings of 18% for the structures considered. Fabricated tees may also save weight in another way. Surveys of as-received product weight reveal that actual weights of hot-rolled shapes are generally 4-5% over theoretical weights, whereas as plates have been measured consistently at within l% of theoretical weight.

Design specifications may not allow fabricators to take full advantage of these weight savings. The DDG-51 Ship Specification for instance, allows fabricated shapes to be substituted for stripped I/T's, but only if the fabricated shapes have sections identical to the I/T's they would replace.

Finally, many mechanized welding methods run at faster speeds than burning methods. Depending on the technology and equipment used for production fabricating may require less shipyard labor. The problem becomes one of overall strategy in evaluating how structures should be stiffened and producing the required shapes in the most cost-and weight-efficient manner.

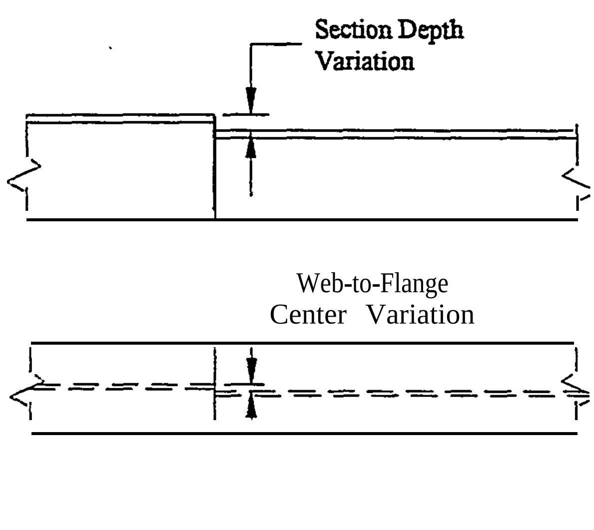

Figure 4. Some Variations Allowed by A-6

APPROACH

Analysis of tee beam manufacturing took these steps:

- Existing and advanced technologies for deflanging I-beams were evaluated
- Technologies for welding tees were evaluated
- Relative economies of the methods were compared
- Small-scale mock-ups evaluated promising technologies as to speed, distortion and quality, and
- Where possible, large scale mockups verified the results of small scale mockup tests.

This approach had to take into account some very practical limitations. First a target population of tee sections was needed for this analysis. To provide a well-understood group, the DDG-51 class vessel was chosen. Currently in production at Bath Iron Works and Ingalls Shipbuilding Division the DDG hull uses thirty different I/T shapes produced from I-beams which range from W6x9# to W20x55#. As shown in Table I, more than 26 km (80,000 feet) of I-beams weighing 701 tonnes (690 long tons [of 2240 Ibs]) are deflanged yielding 527 tonnes (519 long tons) of tee shapes and 174 tonnes (171 long tons) of scrap, resulting in a significant loss (over $90,000 at recent prices).

Second any type of mock-up testing of new technology had to be done on available equipment developed to meet existing needs. Generally, existing equipment is not capable of making long, parallel simultaneous cuts. Thus, laser and water-jet cuts had to be done sequentially in two passes, on relatively short pieces of material. While cut-edge quality and speed could be compared it was difficult to estimate the kind of distortion which might be experienced using these technologies for comparison to that produced by the traditional dual-torch oxyfuel method. Fortunately, plasma-arc cutting equipment was loaned to this project and installed on a production bar stripping gantry, so that beams 12.2m (40 ft) in length could be deflanged.

Finally, an economic analysis Of production costs and rates is limited in the number of potential scenarios treated and relies on some basic assumptions. Review of manufacturer's data can provide much information but the final cost will depend on the implementation of the method and the degree of utilization (duty cycle) actually maintained by production personnel. This project has attempted to evaluate a number of these factors to determine an optimum approach to manfacturing stiffeners. Knowing that local conditions may require different solutions to the same problem a further goal has been to provide enough information to allow the reader to evaluate different situations.

[redacted]

20	55	44.18	10.82	19.7%	20	18	360	19,800	15,904.8	3,895.2
					Total Pieces:	1,716				
						Total Feet:	82,441			
						Total Wgt (#):		1,545,469	1,163,603.1	381,865.9
						Wgt. (LTons):		690	519	170.5
									% Scrap Loss:	25%

PROCESSING AND PRODUCTION CONCEPTS

Two distinct scenarios have been used for processing tee sections. Stripping methods have generally used a batch-type approach with multiple bars being deflanged simultaneously by a gantry moving over the parts, and fabricated tees have traditionally been produced by a continuous method with a two pieces (web and flange) being passed into a fixed welding head to produce a single tee. Stiffener welding gantries, made to simultaneously weld several stffieners to plates, can also be used to manufacture batches of tee shapes.

The advantage of batch processing is greatest when the cost per process insulation is relatively low compared to the cost of the gamy or station. If four I-beams can be processed at once, many of the cost elements per cycle are divided by four. An oxyfuel deflanging gantry is a good example. Torch carriages can be added to a gantry for a relatively low cost. In contrast higher-speed methods like laser cutting may cost 100 times as much as oxyfuel per cutting head and can reasonably be expected to be more cost-effective only in a continuous-process mode, gaining their advantage from higher processing speed.

Continuous processing has been used for many installations where high speeds are achieved and the cost of the process is relatively high Usually, continuous-mode production is not very flexible, as machinery is designed 10 do large volumes of particular sizes, either very heavy sections (e.g. bridge beams) or" very light, as in shapes for mobile home frames produced by High Frequency Resistance Welding (HFRW). The concept of making many different sizes at a shipyard in any kind of "just-in-time" approach is not intuitive. Nonetheless, if the entire volume of stiffening elements is considered it maybe economically feasible to justify more than one machine. Further, the operating range of equipment may be expanded by minor modifications in design.

Beyond the relative merits of batch and continuous processing, other aspects producing stiffeners should be considered. Figure 5 shows the production path horn as-received mill product to the final detail, of three approaches to providing stiffening elements for shipbuilding. Method A is the deflanging, or I-to-T stripping, in which I-beams are received horn steel mills and the flanges are burned off and stock lengths of tees are inventoried for later cutting into structural details. Scrap, averaging 25% of the new material, is generated at the deflanging stage and must be removal rework may be required significant handling is incurred and material must be supplied and inventoried both upstream and downstream sides of the stripping facility, well in advance of production requirements. When the schedule finally calls for production of specific tee elements, the previously deflanged beams are drawn from stock laid out. and cut to the desired length and configuration. Scrap is generated at this stage as well.

Method B shows the fabrication of stock-length tee sections from plate or strip material. Steel bars or strip are provided either by cutting plate or purchasing hot-rolled flats. Scrap may or may not be generated depending on the approach. Flange and web are aligned and fit, typically with substantial manual effort and joined usually by semi-automatic welding methods. For light sections, welds are usually much larger than needed for strength. Significant distortion may occur during welding, requiring rework. Little scrap is generated but handling maybe extensive. Again, material is inventoried both upstream and down stream in the production flow to assure that there are tees available for cutting into detail pieces when schedules require. The final step is the same as done in A.

Tees can also be fabricated from pieces of standard "Universal Mill" bar stock. One foreign shape rolling mill provides such fabricated sections which fit into gaps in the catalog of split hot-rolled I-beams. This only establishes another catalog, and still forces tradeoffs between required strength and final weight because these shapes are still not optimized to the design goals of the vessel. The thicknesses and widths of universal mill ban are suffciently varied so that weight compromises may be less severe than those forced by stripping I-beams to tees. If a supplier uses this approach fabricated tees produce no scrap until the final detail cuts are made.

A and B are fairly well known and used the differences being only of scale. The traditional approach is that tees are produced by method A if there is an I shape with reasonably close sectional properties, and method B is used everywhere else. Because the final use may not be known at the time tees are welded welds are usually designed for 100% efficiency, even though in many applications, welds which join these tees to decks or shells need only be 60-70° efficient.[10]

For production of stiffening elements on a shipset scale, method C is a different approach entirely. All web and flange sub-pieces would be cut to final shape from flat plate, and joined into a "net-shape" stiffener. Scrap is generated only in the plate cutting phase, and handling and inventories could be significantly reduced. Through efficient nesting of material, scrap could be minimized. The main concern is that tracking of pieces is critical to success. The ideal reduction of inventory would have flange and web piece being cut at nearly the same time, and immediately being routed to automatic

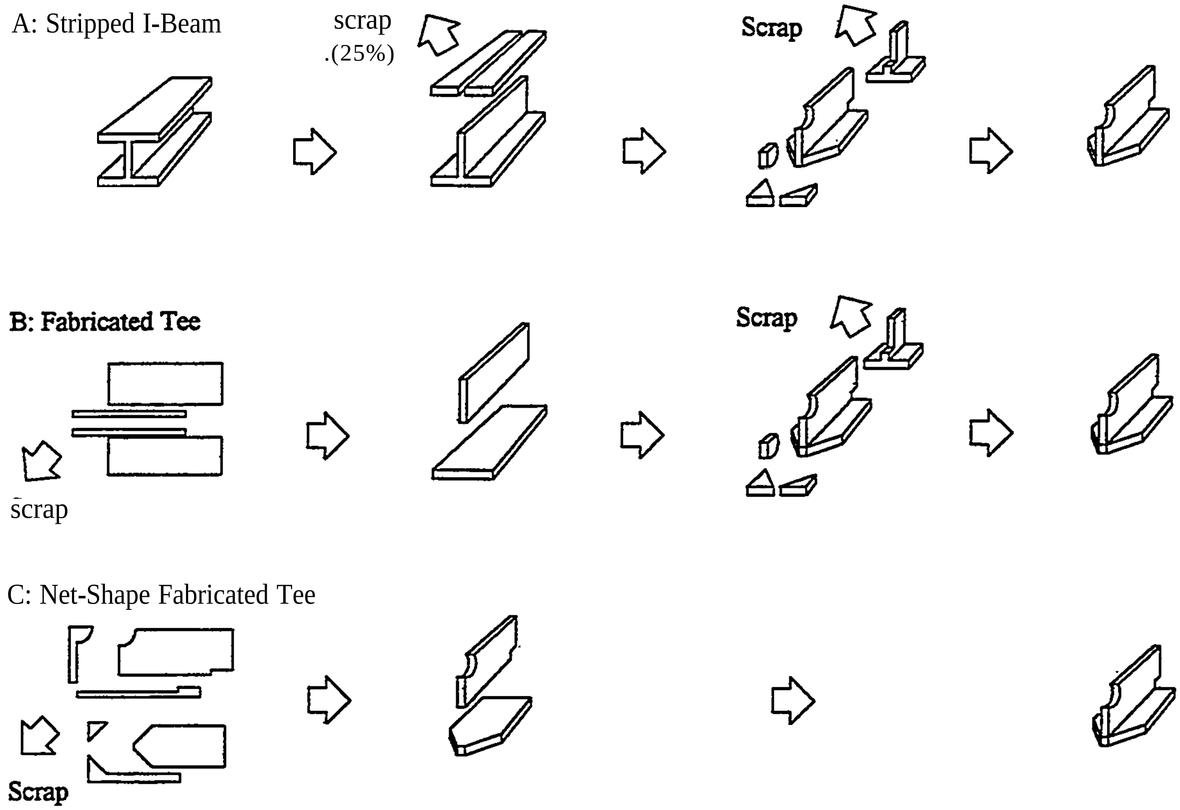

Figure 5. Practices of Tee Stiffener Production

welding workcells. The concept of efficient nesting, however, might require that some inventory of web and flange parts be maintained as the processing of different thickness plates dictated. This implies a thorough method of storage and retrieval on a scale not used before. With the increased use of computraized job tracking and bar-coding on the shop floor, the question becomes more one of execution than one of possibility.

"Net shape" production of tee elements also requires the use of automatic welding equipment to be successful. Manual fitting and tacking must be eliminated and.welding must be reliably done at the highest practical speeds. Through computerized integration of all job factors, including design and welding data as attributes of part identity, the correct size and shape of welds can more nearly match design requirements. New methods, such as laser welding, offer potential for full penetration welding at high speeds with minimum overwelding.

A further demand on equipment flexibility is that in addition to different sizes, many different lengths must be produced. Typically, tee fabrication equipment is used to produce standardized long pieces only.

At first it might appear that method C is not used at all, but that is not really the case. Large and complex fabricated web frames are tee sections nonetheless. The use of method C to produce smaller or shorter tees in any significant volume has not been reported.

An aspect of stiffener production which is seldom considered comes from the fact that a shipyard must buy and inventory a enough I-beams to meet the production rate of a beam stripping fcility. This facility then makes a "second inventory" of shapes which are issued out and processed later into useful ship parts. The cost of the extra material needed and the lead time necessary to support these schedules are difficult to clearly state. A "net shape" approach does away with all of this, but the implementation is no simple matter.

CUTTING AND WELDING METHODS FOR STIFFENER PRODUCTION

The methods review catalogued a number of cutting and welding technologies, emerging as well as traditional, which could be applied to the manufacturing of tee sections for stiffening ship panels. The methods were screened and the more promising techniques identified for further analysis of cost quality and productivity, small-scale mockup testing, and where appropriate, large scale mockup testing.

Machinery for producing welded tee stiffeners should beat least as productive as that currently used for stripping, but more modem methods of deflanging may exist or couid be developed. These methods should be reviewed alongside the potential welding techniques, and the method with the lowest overall cost chosen for production.

This phase attempted to determine

- If a given process can produce a target population of various tee shapes,
- What production rates are possible,
- What acquisition and consumable costs for the equipment are, and
- The dimensional and surface quality the process yields.

Relevant literature and experiences of those in other industries were studied to determine the potential of various methods for producing tee sections. New technologies were considered especially those which promised greater efficiencies. Since there are so many variables in the configuration of a system capable of dealing with shipset quantities of tee sections, a study of this nature must necessarily be qualitative rather than quantitative.

Once methods were identified those most Iikely to produce shipset quantities of tee sections were scheduled for small scale trials, and evaluated to establish modifications might be necessary for making the method into an eficient production tool.

The following methods were selected for review, based on demonstrated success in similar production situations, or, in some cases, on the potential for high speed or high accuracy processing. In the discussions which follow, costs are estimated based on the process equipment at its simplest level, without extensive material handling equipment, In general, the addition of in-feed and out-feed conveyors and stock and scrap handling equipment could add as much as .$500,000 to the costs listed

Cutting Methods

For deflanging of I-beams, the process must cut through the thickness of flange and some amount of material in the radius region between the web and the flange. Flange thickness for the target group shown in Table I ranges from 5.2mm (0.205 in) for the lightest section (W8x10#), to 17.7mm (0.695 in) for the heaviest (W18x60##). Radius ranges from a minimum of 7.62mm (0.30 in) to a maximum of 16.5mm (0.695 in). As shown in Figure 6, the maximum thickness was estimated at the flange thickness plus one-half the amount of the radius. Cutting methods identified for this review are summarized in Table II. A brief description of each process follows.

Oxyfuel Cutting (OFC) is the most widely used method for producing tees from I-shapes. The strong points of OFC are the wide base of experience, inherent flexibility, and low equipment cost associated with the process. Its main disadvantages are low travel speeds (.3-.6 m/min (12-24 ipm) as shown in Figure 7), high heat inputs, and relatively large kerf(with the potential for damaging webs when the flame is too close).

OFC equipment is relatively inexpensive to produce and easy to maintain. When an installation for producing tees has been designed the cost of adding multiple torch carriages is only $2-3k, so that

Table II Stripping Methods

Process	Speed	cost	Consumables	Flexibility	Quality
OFC	0.3-O.6m/min (l-2 fpm)	Low	Gas, Tips	Med	Fair/Good
PAC	0.6-l.8m/min (2-6 fpm)	Med	Gas, Noz., Elctd., Tips, Pwr	High	Good/Exc
LBC	0.3-l.8m/min (l-6 fpm)	High	Gas, Pwr	Meal/High	Good/Exc
AWJC	175-150mm/min (0.25-0.5 fpm)	High	Water, Grit Nozzles	High	
Cold Saw	1.2m/min (4 fpm)	High	Blades, Fluid	High	
Arc Saw	1.5-9m/min (5-30 fpm)	High	Power, Blades	High	**Unknown**

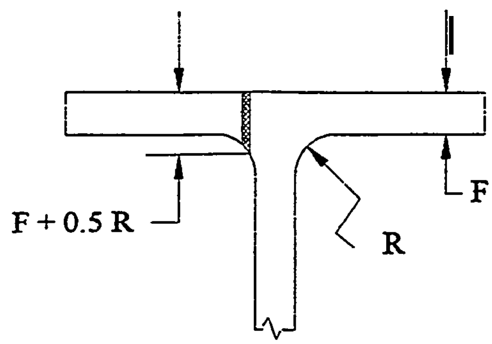

Figure 6. Estimated Thickness of Deflanging Cut

significant parallel processing can be used to reduce the labor costs per foot of processed bar. Fully adaptive control of the OFC process, i.e. dynamic changes to pressures and orifices, has not been explored OFC's low speeds are a disadvantage for increasing the cost and complexity of equipment. As a resulg (OFC suffers from a lack of fine control, and this can lead to a certain amount of rework as a result. fine

Consumables used for OFC consist of oxygen fuel gas, and cutting tips. Fuel gas may be propane, mtural gas, or propylene+based -, acetylene is not widely used for large scale operations today.

OFC can cut any thickness of steel used in stiffeners today. This is in contrast with laser and plasma cutting, where the increase in thickness capacity requires a greatly increased capital cost for equipment.

Thermally induced distortion is the highest in OFC, since the process has the highest heat input. Distortion may be reduced by optimizmion of parameters, use of water sprays, and pre-cambering, but OFC still generates significant quantity of material which requires straightening. Other quality problems arise when a cut is made too close to the web, leaving a scarkd or gouged area which nmst be repaired by welding and grinding.

Plasma Arc Cutting (PAC) provides significant improvements over OFC, especially in speed and reduction of heat input. The process is well understood equipment is rugged reliable, and electronically controllable. Prior to the introduction of oxygen-capable plasma systems, PAC was not a serious contender for use in I-beam defklanging because the tolerance band of parameters which would produce relatively slag-free cutting was too narrow, even though cutting speeds could be generally faster than OFC. This k even more important in beam deflanging than in plate cutting. Since the cut is made through the radius transition from flange to web, one side of the kerf cuts through thinner material than the other side. Any variation in the torch position relative to the web results in a rapid change in thickness to be cut.

Oxygen plasma and inverter-technology power sources have made PAC more attractive. The use of oxygen has resulted in a broader range of travel speeds which produces cuts with minimal slag adhesion. Inverter power supplies offer greater energy efficiency, produce a narrower kerf and are more tolerant of variations in torch-to-work stand-off distance.

Plasma cutting offers the same boost to cutting speed for I-beam processing as for NC plate cutting, with speeds of 2.5 m/min (100 ipm) and faster. Figure 7 shows that speed improvements are significant only in thinner materials (-9.5mm (3/8 in)). As thickness increases, PAC travel speeds drop to values near to those of OFC. For the current range of thicknesses of tee sections in this study, plasma still enjoysaspeed advantage over OFC, and as long as the work mix favors the thinner sections, overall processing times are significantly reduced

Plasma equipment is about ten times more expensive than OFC, but is typically less than one-tenth the cost of lasers, abrasive water jet machines, and cold saws. Inverter-type plasma equipment costs in the neighborhood of$lOK for a unit which will cut all the thicknesses in the target group of tees. To strip one I-beam at least two units are needed more for simultaneous batch cutting.

Electrical power, cutting gases, and torch parts (electrodes and tips) are the major consumables required for plasma cutting. consumable parts life is markedly shorter with oxygen plasma than that experienced by the older nitrogen plasma systems, but

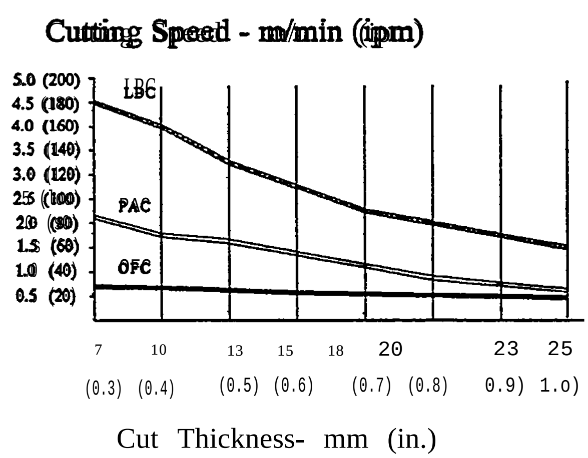

Figure 7. Cutting Speeds for LBC, PAC & OFC

mprovements in cut quality, speed and the wider range of parameters at which slag-free cuts can be made have made oxygen plasma dominant in this field.

PAC is reasonably flexible, although for the Purpose of this study, the ability to cut materials other than steel is a moot point for most commercial ship tees. The penalty for ability to cut greater thicknesses is the aforementioned loss ofspeed, and the need to buy much more expensive equipment capable of processing the greatest thickness, even though these thicknesses may be only a small percentage of the total work mix. Comparatively, since OFC is slow even on thin material, the drop-off of OFC cutting speed with increasing thickness is less noticeable.

As in NC plate cutting, PAC can produce acceptable edge quality. Higher travel speeds possible should produce less distortion than that seen with OFC due to reduced heat input The use of water sprays and pre-cambering could further reduce distortion.

Laser Beam Cutting (LBC)[13 14 15 16]i s is gaining in acceptance in the manufacture of light-gauge materials, and power levels have been increasing while cost per kilowatt has been decreasing. The power density available is the highest of the competing thermal cutting processes, so thermally-induced distortion should be the lowest with lasers compared to any of the other available thermal cutting processes.

Carbon Dioxide (CO) lasers in power levels up to 25 kilowatts are available, although the highest-powered units are seldom used for cutting. Multiple-rod Neodymium Yttrium-Alminum-Garnet (Nd:YAG, often called "YAG) lasers have been produced in versions up to 3 kW, and programs are underway to produce a solid-slab YAG device of 6 kW capacity. Within the distinction of CO_z and YAG, there are several competing technologies, such as RF-pulsed, fast -flow, diode-pumped, slab, etc. Each may offer specific benefits in speed or quality within its power range, and detailed discussion of these is beyond the scope of this paper. YAG lasers maybe used with fiber-optic beam delivery, allowing the laser to be located in a favorable area while the flexible fiber can be deployed in a typical shop atmosphere. This could be a benefit for shipyards, as the special attention to beam delivery required for CO_2 devices is avoided and a greater choice of configurations for tee processing equipment is afforded.

While laser technology is promising, the amount of demonstrated success in heavy-section cutting remains limited and cutting speeds tend to drop off with increasing thickness for a device of any given power level, Considering the high population of relatively light sections used in surface combatants, this may not prove a serious limitation.

There is potential for very high cutting speeds, although there is not a large volume of industrial experience in thick-section cutting to support this claim. In addition attention to factors such as beam quality, the design of nozzles and beam focusing optics is critical. Development in this area has been demand -driven and therefore limited to thinner materials. Nevertheless, speeds of up to 1.25 m/min (4 fpm) were demonstrated in the test phase of this project using equipment clearly designed for thinner sections.

CO_2 lasers at power levels of 1-3 kW cost in the neighborhood of $250,000 while the equipment of 10 kW and higher can cost several million dollars. YAG equipment of 2.4 kW capacity is similarly priced to CO, equipment of equal power. The cost is dependent on several factors, and due to technology growth may change significantly in the near future.

Higher powered laser devices (14-25 kw) are 10-14% electrically efficient so electrical power is a major cost element. Gases, and to a lesser extent nozzles and lenses, are consumable items. Fiber-optic cables are relatively durable, but terminations and couplings are currently expensive to repair. As this technology grows in popularity, costs for maintenance can be expected to drop.

As with plasma cutting laser systems are power dependent so that for a device of any given power output as thickness increases, cutting speeds decrease disproportionately. Thus, the co`st of high-power $C0_2$ devices limits the use of LBC. While high quality cuts with 3-kW devices have been demonstrated in materials 19mm (3/4 in) and thicker, travel speeds are reduced Also, at some point thermal attributes of the base metal begin to dominate the chemical reactions in cutting, and some of the advantages of high power density are mitigated.

For materials up to 6.3mm (1/4 in) thick laser cutting yields near-machined quality surfaces. Translating this experience to thick carbon steel with surface rust and mill scale is a significant challenge.

Cold Sawing[8,17] a machining method, is a relatively low-temperature process, and has been increasingly used for cutting structural shapes to length in cut-off saws. Cold circular saws have provided a high quality, cost-effective alternative to band saws and oxyfuel equipment for transverse cuts. The potential advantages of cold sawing are the production of superior edge quality, the ability to cut arbitrarily close to the web of the beam, and the potential for reduced distortion offered by an essentially non-thermal process. A significant consideration is the residue of cutting fluid which if not removed can affect subsequent weld quality.

Manufacturers claim that cutting speeds up to 1.2rn/min (4 fpm) can be achieved in flat plate cutting. These systems oflen are rated either on volume of material removed or the area of the cut face. Some systems have quoted higher rates, such as 200-400cm^3 (12-24 in') removed per minute, and thus travel speed would depend on blade thickness. Since the saws are very precise, the process may be adversely affected by the tolerances for hot-rolled shapes dictated by ASTM A-6, which allows significant flange tilt off-center flanges, and other dimensional inaccuracies. Equipment may be designed to overcome this, but it will add to the expense.

Cold saw set-ups cost in the neighborhood of $250-500k depending on the amount of material handling equipment. In this case, they are almost always configured with some conveying equipment and the demands of material handling specific to tees may alter this cost range.

Blades are the major consumables for cold sawing, although they may be resharpened several times. Cutting fluid is next in importance, especially considering the impact of increasingly stringent environmental regulations. Chips produced in the process are recyclable, but may require special handling due to the presence of the fluids.

Cold sawing can handle the entire range of thicknesses required but like all processes, cutting speed is a function of the thickness to be cut

Abrasive Water Jet Cutting (AWJC)[18] has been used to cut many "problem" materials with great accuracy, from very brittle ceramics and metals to foam products. For I-beam stripping, the low heat input would produce little distortion but slow production rates and high installation and maintenance costs make it economically unfeasible. The process can cut at speeds UP to 150 mm/min (6 ipm) on soft materials or light gauges of metals. Cutting rates drop to below 25 mm/min (1 ipm) on 25 mm (l-in) thick steel.

Equipment including pumps, intensifiers, distribution systems and manipulators can cost up to $500K Since pressures up to 50,000 psi are used wear is significant and maintenance costs are high.

Water and abrasive grit (typically garnet) are the major expendables. Although garnet is not a particularly hazardous material, it forms a sludge with the cut metal particles in the water tables. This is not recyclable because of the metal content and incurs a fairly high disposal cost.

AWJC is flexible in that it can cut a wide range of materials, but application of the process is limited due to its low trowel speeds. Excellent cut surface quality is produced by AWJC, and distortion to parts is minimal.

Arc Sawing19 is a recently-developed technology that uses a spinning metal disc, or blade, which transfers current from its edge to the work piece. Extremely high currents, several thousand amperes, are **used, and incredibly high cutting speeds are possible.** The equipment runs completely submerged in water, and all current installations of this equipment are being used to cutup decommissioned nuclear reactor vessels, limiting the amount of experimentation which might be carried out at existing installations. Little work has been done to establish the applicability of this equipment in other environments, however, the manufacturer reported a test in which an 203mm (8 in) diameter high nickel alloy (625) round bar was transversely CUC to compare with the use of abrasive cut -0ff saws. The abrasive saw took 10 minutes to make the cut while the arc saw severed the bar in 8 seconds. Quality of the cut face was not as good as that produced by the abrasive method and no development work was ever undertaken to determine if edge quality mild be improved.

Based on work done on flat plate, speeds are estimated to be nearly 9m/min (30 fpm) on 4.7mm (3/16 in) material, dropping down to 1.5m/min (5 fpm) on 25mm (1 in) thick steel.

This equipment would cost upwards of $750k not counting any material conveying systems. Handling equipment would have to be capable of coping with the high electrical currents involved.

Electrical power (6,000 Amperes per head) is the primary consumable, but blade usage is a significant factor. Blades cost $250 each and blade life is estimated at 150-300m (500-1,000 ft) of cut. At best for 16m (49 ft) long I-beams, each pair of blades would wear out after 20 cuts, thus deflanging 1700 beams would consume 170 blades at a cost of $42,500.

It is not known how the geometry of I-beams would affect cutting properties and cut-edge quality. In contrast with heavy, flat plate cutting, I-beams present a non-uniform cross-section (see Figure 6.) to the blade. When high currents travel through non-symmetrical paths, magnetic flux from the current interacts with the magnetic flux of the arc, causing a phenomenon called "arc blow." Arc blow is often seen in welding at high currents, and appears as erratic arc action resulting in poor quality.

Welding Methods

Welding processes reviewed are summarized in Table III. More traditional welding methods such Gas

Table III. Welding Methods

Process	speed	cost	consumables	Flexibility	Quality
GMAW/FCAW	0.6-l.8m/min (2-6 fpm)	Med	Wire, Gas, Power	High	Exc
GMAW-P	0.6-3m/min (2-10 fpm)	Med/High	Wire, Gas, Power	High	Exc
SAW	0.6-2m/min (2-7 fpm)	Med/High	Wire, Flux Power.	High	Exc
LBW	0.9-3m/min (3-10 fpm)	High	Wire, Power	Meal/High	Exc
HFRW	-60m/min (200 fpm]	High	Power, Coolant"	Low	Exc

Metal Arc Welding (GMAW), Flux-cored Arc Welding (FCAW) and Submerged Arc Welding (SAW) are well documented and have an established range of typical procedures, thus discussion is purposely limited. Although some work has been done with pulsed gas metal arc welding (GMAW-P) for high speed applications, both that method and the field of Laser Beam Welding (LBW) are relatively untried in this form of manufacturing: i.e. long, heavy sections with high production volume. Figure 8 shows estimated welding speeds for GMAW (FCAW is nearly the same), SAW, and LBW. Speeds for GMAW and SAW are based on fillet welding to achieve 100% efficient welds (weld strength equals base metal strength). LBW speeds are based on achieving full penetration welds (50+% penetration from each side)[24]

Gas Metal Arc and Flux Cored Are Welding (GMAW/FCAW)[20] have been widely used to produce fillet welds with mechanized equipment. Flexibility and quality are outstanding and equipment is relatively inexpensive, reliable, and readily available. Travel speeds will vary with the size of the weld required and will largely depend on the deposition rate of the electrode and welding parameters chosen. Anew variation of the process is the use of "Metal-cored" electrodes, which have been seen to offer higher productivity with excellent arc stability and weld cosmetics. Major consumables are welding filler metal, which generally costs on the order of $2.20/kg ($1.00/lb), and shielding gas.

Pulsed Gas Metal Arc Welding (GMAW-P), uses very specialized pulsed power supplies to achieve extremely high speeds 3-4.5m/min (120-180 ipm).[21,22,23] In general, weld sizes at these speeds have been small, and base plates farily thin, so it is not known if this approach will provide the flexibility to perform large-scale welding of ship-sized structural elements, especially in the commercial arena. Costs of the consumables are the same as above, but the equipment is not widely available, and is more expensive than traditional GMAW power sources. These speeds are competitive with those achieved by high power lasers, and double those offered by submerged arc welding.

Submerged Are Welding (SAW) has been used to produce more fabricated tee shapes than any other welding method. The process is well understood, and although equipment is generally more expensive than GMAW/FCAW setups, it is still reasonably priced. The process offers good flexibility and generally faster travel

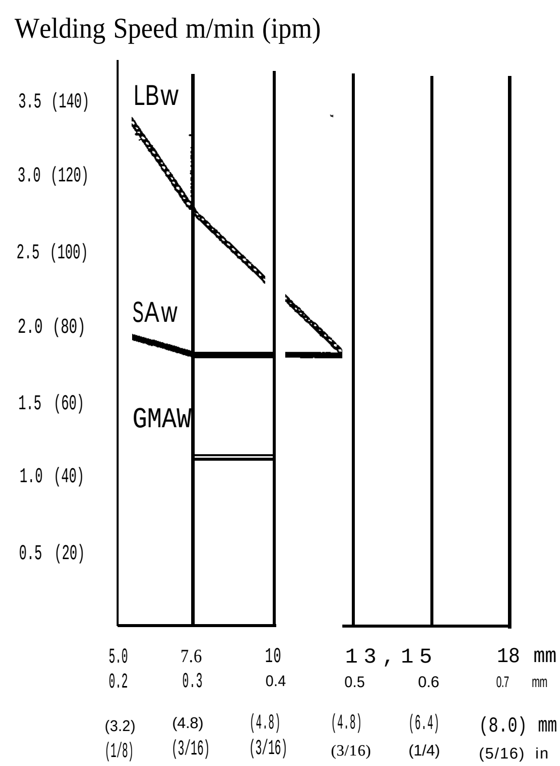

Figure 8. Welding Speeds for LBW, SAW, & GMAW

speeds than “open-arc” methods, especially for large welds, through the use of multiple wires. Other advantages of SAW are the low level of smoke produced and the lack of significant arc radiation, although these not are major considerations for highly mechanized equipment. Higher travel speeds result in reduced distortion although straightening by some means is required. This is often done in-process, by an in-line heating torch applying balancing heat to the opposite edge of the web. Major consumables for SAW are filler metal and flux and are similar in overall cat to those required for GMAW and FCAW. SAW can produce welds with excellent soundness and metallurgical properties.

Laser Beam Welding (LBW),[24,25] has grown in use in the last decade, producing high-quality, high speed welds with low distortion on a wide variety of materials. The fundamental disadvantage of the process is high equipment cost, but prices may drop as systems become more widely used. The cost of devices with power levels sufficient for fast processing of thicker parts has some impact on consideration of lasers for commercial ship work.

In fabricating tees, one significant fact associated with laser welding as opposed to cutting is that penetration by one beam through the entire thickness is not needed. Two opposing beams need only produce as much penetration as the design requires, something more than 50% if full penetration is required. One high power laser may cost more than double the price of two devices of half that power

Laser systems can cost from $300K to $3,000k, but high-powered devices can make effective use of beam splitters, increasing the number of welds which can be made simultaneously. Thus, timer material could be processed in multiple parallel operations, or the system re-configured for single processing of thicker work pieces. Card review of the of the whole production scenario is required.

Laser welding at speeds over 4m/min (160 ipm) is possible for thinner (<4.7mm (3/16 in)) sections included in this analysis. Travel speeds drop off for materials over 12.7 mm (1/2 in), especially with lower powered devices, but power level is not the only criterion for evaluating lasers. Beam quality, spot size, and brightness, can have bearing on an application.

Electrical power is a major consumable. Plasma suppression gas (helium) is usually and it is expected that some filler metal would be needed to provide an acceptable weld profile.

Laser welding should yield the lowest overall distortion in as-welded parts, due to its very high energy density and fast welding speeds.

High Frequency Resistance Welding (HFRW) has produced large amounts of lightweight I-beams for truck trailers and mobile homes.[6,7,31] High current at high frequency is passed between web and flange connections, heating the junction quickly to forging temperature. Pressure rollers force the parts together for full-penetration welds. Machinery is large and expensive (costing millions of dollars), and suited to production of high quantities identical shapes, but runs at extremely high speeds, up to 61m/nin (200 fpm). The method is generally used on lighter materials (9.5mm (3/8 in) and less), and works best with coiled strip, handled by unloaders and on-the-fly coil splicing stations. HFRW was recently used for producing several lightweight (8.92kg/m (6#/ft) and lighter) sections for later-flight CG-47 class vessels, and should be considered when large quantities of light weight sections are needed. HFRW is not able to process the full range of thicknesses of the DDG group of stiffeners.

COST ANALYSIS

To determine a baseline cost for producing the target population of I/T shapes, the literature was searched for prior work relating to industry experience in I-beam stripping. To validate this information a time study of beam deflanging using the OFC process was made.

Conducted fourteen years ago under funding by the NSRP, the Semi-Automatic Beam Line (SABL) Feasibility Study included a limited review of the cost of I-beam deflanging. The SABL study compared the productivity of “standard” methods, measured at a shipyard to that of a proposed highly mechanized facility for all processing of structural shapes, including web frame fabrication angle and channel processing, end cuts, copes and bevels. The proposed Semi-Automatic Beam Line consisted entirely of improvements to conveying and material handling equipment. AU cutting including beam deflanging was done by the OFC process. There was no proposal to change the processing technology or process parameters used in any of the "standard” methods, and the substitution of fbricated tees for stripped I-beams was not suggested The SABL study did not go into specific details for any of the functions, naming only two cost elements, '‘handling” and “processing.” Furthermore, the study did not look beyond the boundaries of the processing facility. The issue of material transport into and out of storage was tacitly treated as a constant. Handling referred to movement of material within the facility only, and handling functions were not reported or compared in any detail.

Finally, neither overall product quality nor rework were mentioned in the SABL study.

The SABL study did provide basic cost data associated with using the OFC process for deflanging 5,000 I-beams per year. Using the SABL study data as a base-line, this project analyzed I-beam stripping functions in greater detail, to verify that the current cost of deflanging by the OFC process was similar to the cost of the "Standard" method reported by the SABL study, and to evaluate areas where process improvements might have the greatest benefits.

Figure 9 shows this primary comparison the "Standard" method referred to in the SABL study (OFC deflanging of batches of I-beams) required approximately 1.3 labor hours (Lhrs) to strip flanges from one I-beam. The "Std verified" data (current practice reviewed in this report) showed a similar time per beam, when all in-process handling (rigging on and off burning tables, set-up, and scrap removal) was added to the actual OFC burning time under "processing." "Handling" for the standard and the SABL comparison referred to the time spent on moving material to and from the process, within the facility. This was documented at 0.286 Lhrs per beam for the standard method and less than 0.2 Lhrs for the SABL method. For the verified standard data "handling" referred to movement of material from storage areas to the facility (approximately 0.57 Lhrs per beam).

While the SABL study concluded that handling and processing times could be substantially reduced, it is significant to note that the ratio of handling time to cutting time did not change (Figure 10). Although handling (as treated by the SABL study) was reduced by 40% (from 0.286 down to 0.171 Lhrs), it remained 18% of the total cost of producing I/T shapes.

Since the SABL methodology did not propose to change operating parameters of the OFC process, the total time for burning flanges from the 5,000 I-beams should be the same for both "Standard" and SABL. The reduction of 41% in processing cost (from 1.35 down to 0.8 Lhrs/part was not identified as the result of changes to OFC process parameters. Thus, the ratio of processing to handling time should not be equal, unless some time-related process elements, such as setting up and scrap removal, (which are really handling functions), were also included in "processing" by the SABL study.

Since any comparison of the relative cost of the various new alternatives should include the entire range of functions, it is necessary to break down the verified data into greater detail and include information about the amount of rework, as shown in Figure 1l Rework consists primarily of straightening, but includes a lower percentage of labor to repair damage to tees if the cut has come too close to the web. Straightening is driven by an internal standard which allows maximum camber equal to half that allowed by ASTM A-6 for tees. Since the tees are substantially stiffer than the plates to which by are joined camber must be kept to a minimum to allow ship units to be accurately built. A-6 specifies allowable camber for tee sections solely as a function of length and 15.2m (50 ft) tees are allowed31.7mm (1.25 in) maximum. Since structural shapes are supplied to ASTM A-6 requirements, it has been used as a convenient starting point especially when deflanging of tees has been subcontracted. The current internal standard was based on the experience that all subsequent phases of ship structure fabrication proceed more quickly when straighter tees are provided. The decision as to the output tolerance of the processing system can change the rework percentage greatly. If the A-6 guidelines were followed exactly, only 10% of the parts would need straightening. At a tolerance of one-half of the ASTM allowed value, 50% of parts produced by OFC typically will need straightening.

As a comparison to the standard and verified batch-mode OFC stripping, Figure 12 shows a percentage breakdown of the labor in continuous submerged arc welding[28]. Rework is not added since experience has shown that this equipment can consistently produce accurate tee sections.

Projected Costs

To provide a cost comparison of fabricating to stripping, seven different hypothetical production scenarios were generated. Four approaches to I-beam deflangiug were compared to three welding scenarios.

I-beam stripping concepts evaluated were the standard oxyfuel cutting (Std-OFC) practice, re-equipping OFC batch-processing gantries with plasma-arc cutting capability (Batch-PAC), continuous-processing plasma-arc cutting (Contin-PAC), and continuous processing laser beam cutting (Contin-LBC). Cutting speeds for these methods were arrived at by estimating the thickness to be cut as the flange thickness plus one-half the radius of the transition of flange to web (Figure 6). This yielded a range of 7.62mm (0.30 in) to nearly 25.4mm (1.0 in) for tees used in the DDG-51. Manufacturers' data and other published information were consulted to estimate cutting speed for each thickness, as shown in Figure 7.

Three welding scenarios were all considered as continuous-processing tee fabricating machines: submerged arc welding (SAW), gas metal arc welding (GMAW), and laser beam welding (LBW). Equipment manufacturers and other sources were consulted for performance data shown in Figure 8.

[redacted]

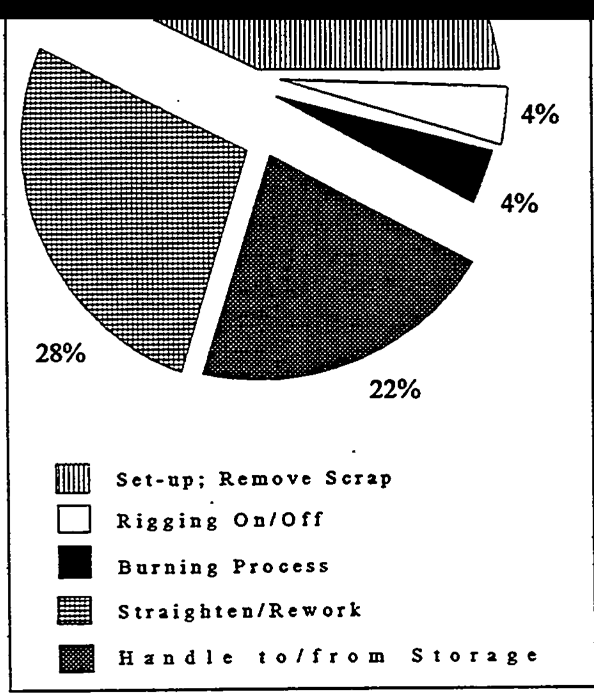

Figure 11. Functions in Batch OFC

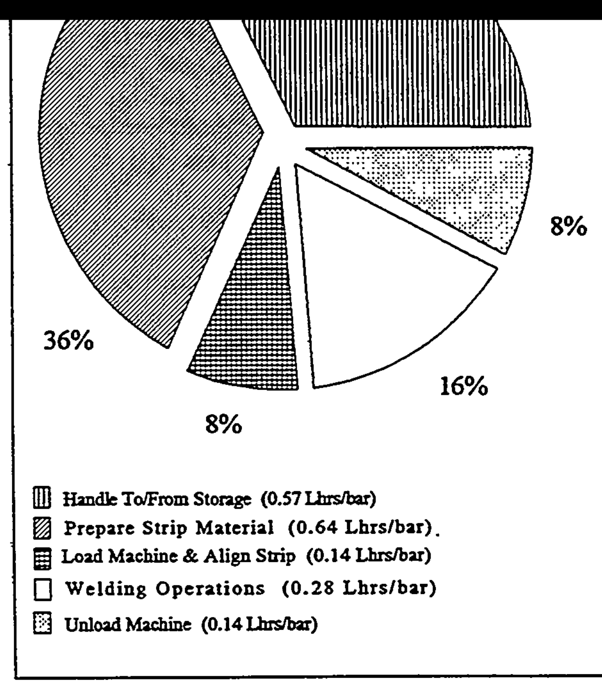

Figure 12. Functions in Continuous SAW

In most cases, for other than laser and plasma processes, these values are well documented-and easily verified by virtue of many successful applications. The use of PAC, LBC and LBW in applications of the indicated thickness range and particular geometry has not been reported so that estimates of expected rates have been made based on available literature.

A number of baseline criteria were established.

- Capital cost of the equipment was not considered.
- Fina costs were the summation of production costs, including handling times.
- Cutting speeds were based on thickness of the flanges plus half the radius of transition from web to flange.
- Required weld size was based on the thicknesses to be joined, and full penetration welds were not assumed except for the case of laser welding, which also assumed small-sized reinforcing fillets.
- Based on experience, rework was not factored into the welding scenarios.
- Cutting methods had rework added in at the experienced rate of the verified data for standard OFC, and half that for the other cutting methods.
- A standard rate of 4 labor hours per plate was used to calculate processing time to produce strips for tees from plates. The total of flange and web widths plus kerf was used to estimate the number of plates required and the scrap generated in this step.

Based on these assumptions, a production cost sensitivity analysis was generatd comparing laker cost material cost and machine utilization variations as major elements in overall cost. Labor rate was factored in steps from $15/hr to $40/hr. Material costs were figured from $0.08/kg ($0.18/lb) to $0.136//kg ($0.30/Ib). Steel cost was treated as the same for both plate and shapes. The price of plates and shapes can vary widely depending on factors such as quantity, lead time, and market demand, to name only a few. With a competitive steel market and the recent emergence of mini-mills, there is pressure on major steel producers to control costs.

In assessing the effect of varying duty cycle, for batch processes, the experienced standard data was used throughout so the lines for Std-OFC and Batch-PAC are constant. Since any machine is profitable only when it is used however, duty cycles from 50% to 95% were calculated for the continuous-process implementations. Considering that a tee fabricating machine usually only requires a 15-second delay between finishing one section and starting the next the 95% maximum was somewhat conservative[28].

As a further attempt to consider these scenarios on a reasonably equal footing, the travel speeds of oxyfuel cutting were based on manufacturer's charts, nearly two feet per minute in most cases, and were substantially higher than those used in current production. Since the burning time in the current process amounts to only 4% of the total labor per piece, there is no substantial reduction in overall costs from the calculated increase in speed.

Once this data was entered time required to produce the target group of tees was generated, and labor cost, material cost and machine utilization variations were varied to yield several overall cost. Tables IV, V, and VI show the detailed results of the time and cost comparisons, and Figures 13, 14, and 15 provide the information in graphical form.

This analysis yields these conclusions.

- In every case, the overall cost to fabricate was lower than the cost to ship, frequently by as much as 30%.
- The reason for the large difference is the loss of 25% of purchased material as scrap in the cutting operations.
- Even if processing scrap is not considered fabricating methods are still lower in cost.
- Laser processes show the lowest cost in each review, but there is little practical experience to back up the performance estimates.
- Of the traditional processes, submerged arc welding shows the lowest overall cost in each scenario, thus it is not surprising that this process has the greatest industry experience in the fabrication of tee sections.

The chart shown in Figure 16summarizes these conclusions. Batch-type oxyfuel cutting and continuous submerged arc welding processes have a considerable experience base throughout the industry. The laser processes, whether cutting or welding, have not been used for work in this manner, so the data is predictive, and may not be realized in production. Additionally, lasers cost orders of magnitude more than SAW or OFC equipment and since capital costs have not been included this may skew the results depending on the expected life span, maintenance, and other costs associated with laser equipment.

Further, material is the dominating cost for all the methods, and reduction of scrap is a major factor in the savings. Total material cost for the shipped product is very nearly equal to the total cost of the fabricated tee. Considering strictly labor, the greatest potential of the continuous methods is the reduction in set-up and handling labor. Even without rework total cost for deflanging still exceeds that of fabricating.

Table IV. Processing Cost (x$1000)vs. Labor Rate (@ $.22/lb and 95% Duty Cycle)						
	Labor Rates, $/hr					
	15	20	25	30	35	40
Std OFC	404	425	446	467	488	510
Batch PAC	394	411	429	447	464	482
Contin PAC	377	390	402	415	427	440
Contin LBC	369	379	389	399	409	418
Contin SAW	280	296	311	326	342	357
Contin GMAW	289	308	325	344	362	381
Contin LBW	276	289	303	317	331	344

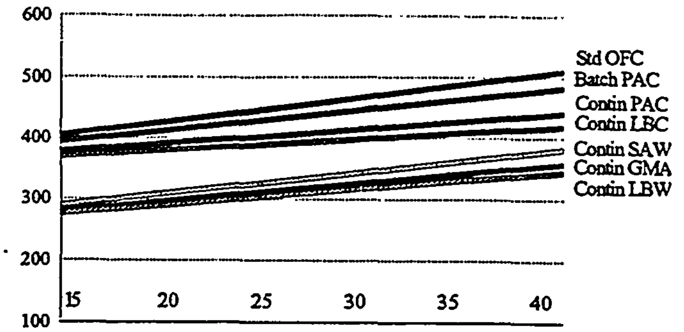

Figure 13. Processing Cost (x$1000) vs. Labor Rate ($/hr)

Table V. Processing Cost (x$1000) vs. Steel Cost (@ $35/hr and 95% Duty Cycle)							
	Steel Cost						
$/kg	0.4	0.44	0.48	0.53	0.57	0.62	0.66
$/lb	0.18	0.2	0.22	0.24	0.26	0.28	0.3
Std OFC	427	457	488	519	550	581	612
Batch PAC	403	434	464	496	527	558	589
Contin PAC	365	396	427	458	484	520	551
Contin LBC	347	378	409	440	470	501	532
Contin SAW	299	320	342	363	384	406	427
Contin GMAW	320	341	362	384	405	426	448
Contin LBW	288	309	331	352	373	395	416

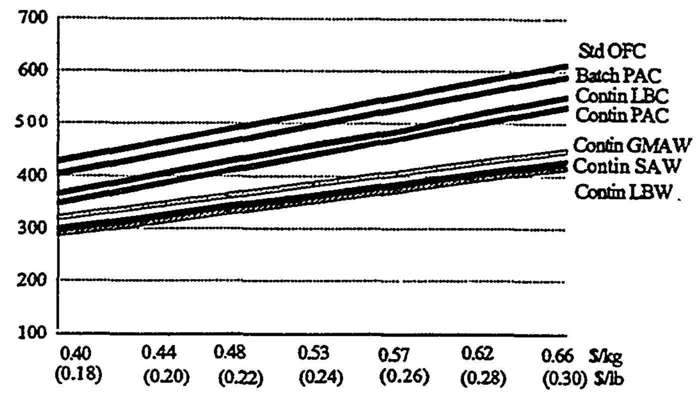

Figure 14. Processing Cost (x$1000) vs. Steel Price

Table VI. Processing Cost (x$1000) vs. Machine Duty Cycle (@ 0.49/kg ($0.22/lb) and $35/hr)							
	Machine Duty Cycle						
	0.5	0.6	0.75	0.8	0.85	0.9	0.95
Std OFC	488	488	488	488	488	488	488
Batch PAC	465	465	465	465	465	465	465
Contin PAC	460	448	437	434	431	429	427
Contin LBC	424	419	413	412	411	410	409
Contin SAW	372	361	350	348	346	344	342
Contin GMAW	411	394	377	373	368	365	362
Contin LBW	351	344	337	335	333	332	331

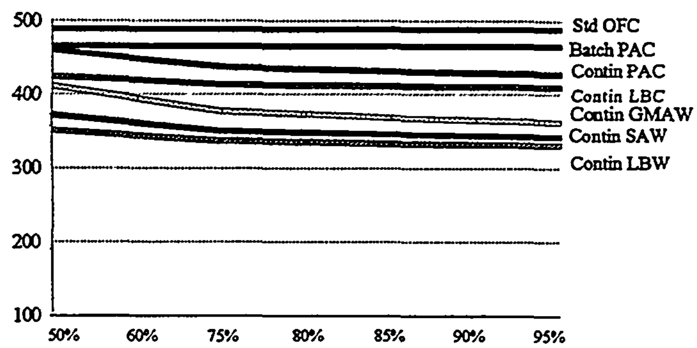

Figure 15. Processing Cost(x$1000) vs % Duty Cycle

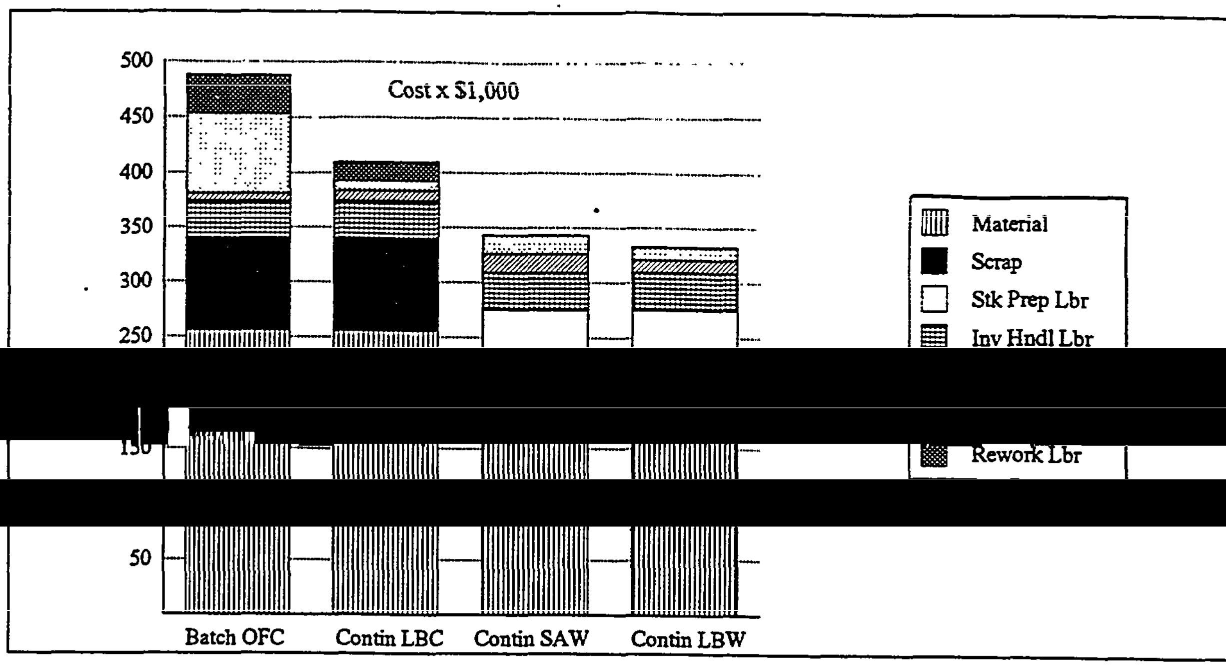

Figure 16. Cost of Batch OFC vs. Continuous LBC, SAW, & LBW

MOCK-UP TESTS

Where appropriate equipment was available, mock-up tests were conducted to test methods for this review. Processing speed and cut quality were evaluate and distortion induced by the process was measured when possible. In many cases, existing equipment was not configured to do a close approximation of a stripping cut or to make tee-section welds. In most cases, only one cutting head or welding head was available, so the stripping or welding operation was done in two sequential operations. This provided some degree of judgment about how the process might perform if adapted to the task of producing tee shapes, although the effect of two simultaneous cuts or welds could not be fully proved. sma11-scale mockups were used to establish parameters for a given speed and quality, and large scale mockups were used to evaluate distortion. The ability to do large parts was limited. Abrasive water jet cutting was evaluated to determine if beams deflanged by a non-thermal process would show distortion due to the release of residual stresses which might be present after hot-rolling.

To provide a standard section for cutting tests, wide-flange beams, W6X20#, were used. This I-beam has a flange thickness of 9.5 mm (3/8 in), and a radius transition from web to flange of 7.62mm (0.30 in), which is in the mid-range of weight and thickness of the target group. These were cut to the maximum length possible for processing at the given facility. Most test pieces were only 600mm (2 ft) Iong, but a few 2.4m (8 ft) pieces were cut. Laser tests were made using lasers of as many different types as possible.

Since the traditional welding processes are well document, only two welding tests were performed. Using a CO_2 laser, two tees. were produced one welded with filler metal, and one welded autogenously (no fiIler metal added). The tee shape was approximated by using 9.5x152mm (3/8x6 in) flat bars for both web and flange. Since the 6x20# I-beam has a 6.3mm (1/4 in) web, this using thicker material was somewhat conservative, reqiring greater weld penetration.

The mock-up tests are documented in greater detail in the NSRP project report, which includes appropriate photographs of the test pieces.

The following small-scale mock-up cutting tests were performed

- Laser cutting of 600mm (2 ft) sections at Applied Research Laboratory, PennState University, using 2.4kW YAG and 1.5 kW $C0_2$lasers,
- Laser cutting of 2.4m (8 ft) sections at ARL using the 14 kW CO_2laser;
- Laser cutting of 600mm (2ft) sections using the kW GE Fanuc CO_2laser at Edison Welding Institute;
- aser cutting of 600mm (2 ft) sections using a 3 kW YAG laser at Hobart Laser Products;
- Abrasive water jet cutting of an 2.4m (8 ft) section at Laser Applications Inc.; and

l OxY-fuel cutting of 2.4m (8 ft) sections at Bath Iron Works.

The following large-scale mock-up cutting tests were performed

l Oxyfuel cutting of 12.2m (40 ft) sections at Bath Iron Works, and

•] Plasma-arc -cutting of 12.2m (40 ft) sections at Bath Iron Works.

The following large scale welding test was performed

. Laser welding of 6.lm (20 ft) sections using the 25 kW CO_2 laser at Stardyne, Inc.

Summary of Mock-up Tests

For most laser and plasma cuts, edge quality was nearly as good as that attained with oxyfuel processes, and for most cases, higher travel speeds were noted than those used for traditional burning.

In general, the processes tested performed at speeds lower than originally estimated Typically, this was due to the difficulty of estimating cutting performance radius at the flange to web transition.

Abrasive water jet cutting produced no measurable distortion in a 2.4m (8 ft) but these pieces were too short to evaluate distortion with any process.

PAC of 12.2m (40 ft) sections resulted in approximately half the distortion produced by OFC.

For both OFC and PAC, water sprayed on the parts being cut will reduce distortion by nearly 50%.

Autogenous laser welds in 6.lm (20 ft) parts produced little distortion when filler metal was added to provide fillet reinforcement< distortion increased.

Distortion measurements taken are summarized in Table VII. The use of 2.4m (8 ft) sections did not provide enough length to gain much insight into potential distortion which might be produced by laser cutting. The oxyfuel result for 2.4m (8 ft) parts is contradictory, but the numbers are so small that it is difficult to draw a valid conclusion.

Water spray is a useful method for reducing distortion. A trickling stream from a small nozzle positioned immediately behind the cutting head gave a better than 50% reduction in camber for both the plasma and oxyfuel processes.

CONCLUSIONS

Scrap material from the deflanging process averages 25% of material purchased. Table I. shows that the deflanging operation generates 172 tonnes (170 long tons) of scrap with the amount of scrap per item varying from 20% to more than 30%. At 0.53/kg ($0.24/Ib), this is a loss in excess of $90,000.

Processing costs for fabricating tees are generally lower than for stripping I-beams. Welding methods and machinery can operate at higher speeds and duty cycles than traditional batch-type oxyfuel stripping gantries. Also, in the fabricating operation the production of web and flange strips results in scrap on the order of only 5% by weight of purchased material hence there is a large reduction in material cost when fabricating is compared to stripping.

Handling is a major cost driver for both fabricating and stripping Operations. Material handling within the shipyard to support tee stripping can amount to more than 70% of labor cost. Thus any increase in cutting process speed may drop overall costs only slightly. In stripping, one piece is brought into the facility, and three pieces must be removal , only one of

Table VII. Distortion Measurements

Process	Measured Camber mm (inches)				
	2.4m (8ft) Dry	2.4m (8ft) Water	12.2m (40ft) Dry	12.2m (40ft) Water	6.lm (20ft) Welded
AWJC, single cut		o			
LBC (14 kW CO_2 single cut	1.5 (1/16)				
OFC, single cuts	0.8 (1/32)	1.5 (1/16)			
OFC, double cuts	3.2 (1/8)	3.2 (1/8)	118 (4-21/32)	55.5 (2-3/16)	
PAC, double cuts			70 (2-3/4)	30 (1-3/16)	
LBW, autogenous					4 (5/32)
LBW, with filler metal					14.3 (9/16)

them a useful product. When tees are fabricated however, two pieces are brought in and only one is removed. Most tee fabricating machinery is highly mechanized to reduce handling, and conveyor systems are a major part of the capital cast of such equipment.

Continuous-process machines can offer significant cost reductions over batch-type methods. Due to more efficient in-process handling, costs are lower even though four operators may be required (batch-type oxyfuel typically requires two). Large tee beam fabricating machines align parts accurately, and provide in-process straightening, resulting in minimal rework.

The plasma-arc cutting process produces less distortion than the oxyfuel method. Test beams (12.2m (40 ft) long) stripped using PAC showed camber to be reduced by 50%, compared to beams cut by the oxyfuel process.

A light water spray reduces camber distortion significantly. On the 12.2m (40 ft) test beams, for both oxyfuel and plasma arc processes, a trickling stream of water directed immediately behind the cut reduced final camber by 50%, compared to beams cut without added water spray.

Capital and maintenance were not included in this cost analysis and could have significant affect on any decision as to overall processing strategy. Since the capital acquisition cost will depend on the work mix and specific conditions of individual sites, this analysis focused on operational cost of processes only.

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